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## Sustainability and LCA in engineering education – A course curriculum

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### Abstract

Educating engineering students in sustainability is becoming increasingly important since engineering is expected to play a vital role in solving the sustainability challenges facing us. At the Technical University of Denmark this awareness is visible in the strategy where sustainability is expected to be an integrated part of all study programmes. The division for Quantitative Sustainability Assessment (QSA) aims to provide this competence to the DTU students. QSA focus mainly on Life Cycle Assessment based methods but have designed a course curriculum that can provide different levels of sustainability competences to students with a progression of complexity from the bachelor to the master or even PhD level. This role is unique since LCA is not systematically a component of engineering studies today. We present and discuss our experience with attempts to integrate LCA and life cycle thinking in an educational curriculum to teach sustainability broadly to engineering students at DTU. A main challenge is how to integrate the teaching into study programmes and eventually how to accommodate an increasing number of students on the individual courses.

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**Keywords:** Course progression; teaching strategy; Life Cycle Assessment

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### 1. Introduction

Sustainability is becoming an increasingly important topic for companies, policy makers, and civil society to address. The United Nations (UN) Sustainable Development Goals (SDGs) [1] define an ambitious common agenda for the global society, and engineers have an important role to play in implementing this agenda by 2030. The Queen Elizabeth Prize for engineering report 2015 (<http://qeprize.org/report>) investigates how more than 10,000 non-engineers from 10 countries perceive engineering and engineers' potential for solving the world's problems (in this context specifically environmental, social and infrastructural challenges). Engineering is seen as a key driver of progress and innovation, and 57% of respondents consider engineers to play a vital role in solving the sustainability challenges that humanity will face in the years to come, making it the most important role of the engineer [2]. The 17 SDGs define a global vision for sustainability, and for many of the goals

engineers must play a central role in meeting them, e.g. smart cities and infrastructures (SDG no. 11), clean water and sanitation (SDG no. 6), clean energy (SDG no. 7) and sustainable production (SDG no. 12). Providing viable solutions for the problems related to reaching sustainability on multiple scales, however, requires that engineers are educated and well-trained in developing and applying methods to assess and implement sustainability, along with gaining a global perspective [3, 4]. This encompasses applying a holistic perspective where the whole life cycle of products and systems as well as a range of different impacts are addressed as a means to avoid problem-shifting and sub-optimisations. Therefore, 'sustainable engineering' will eventually equate with 'good engineering' [5], and sustainability education needs to turn from "nice to have" to "need to have".

In this paper we provide an overview of the course curriculum of a division at the Technical University of Denmark (DTU) to address different levels of sustainability education for engineers. Our special focus is on teaching Life

Cycle Assessment (LCA) as a central component of engineering education today. We present and discuss our experience with and attempts to integrate LCA and life cycle thinking in education to teach sustainability broadly to engineering students at DTU.

## 2. Sustainability teaching strategy at DTU

### 2.1. University level

DTU has around 11,000 engineering students of which 65% aim at a master level education. Each year, about 2000 engineers graduate from DTU ready to enter their working life. With the previously mentioned high expectations of engineers, competencies within sustainability will be a clear competitive advantage considering today's societal challenges. It is therefore crucial that each of these students has the relevant competences in sustainability. The DTU board of governors is aware of the importance of sustainability. Since 2013 it has been part of the DTU strategy that DTU study programmes are designed to ensure that sustainability is an integrated part of the education of every engineer. However, this strategy has yet to be systematically implemented in all educational programmes at the university similarly the life cycle perspective and the potential variety of assessable impacts are often overlooked.

### 2.2. Teaching strategy of Quantitative Sustainability Assessment (QSA)

The division for Quantitative Sustainability Assessment (QSA) is part of the Department of Management Engineering at DTU. In terms of teaching LCA and Life Cycle Engineering QSA is the most prominent group at DTU. In its research the QSA division focuses on developing methods and tools to quantitatively assess sustainability from a life cycle perspective. There is no dedicated master's programme for sustainability assessment, but as shown in the following, QSA teaches courses that are part of or may form part of several master's programmes. It is a vision of QSA to be the driving force in education of quantitative sustainability assessment at DTU, and the division aims to play a leading role in developing educational offers in collaboration with heads of master's programmes and teachers. All engineering students at DTU must obtain a relevant level of competences within understanding and quantitatively assessing sustainability. Two levels of competences are suggested to meet this objective: generalist competences (basic level) and specialist competences (advanced level). The definition of these levels and the development of the curriculum is founded in the six levels of Bloom's taxonomy: knowledge, comprehension, application, analysis, synthesis, and evaluation. At the same time the content becomes more detailed as the curriculum progress, see e.g. [6] for a similar approach.

QSA's course portfolio can provide these competences at both levels and it is suggested that at least one course should be followed at both bachelor and master level. Previous takes

on our teaching strategy have been presented and published [7].

## 3. QSA Course curriculum

The overall course curriculum at QSA is outlined in Figure 1, where the variety of sustainability-related courses are described. The specialization level increases toward the bottom of the figure. Table 1 provides a more detailed overview of the content and progression of the courses.

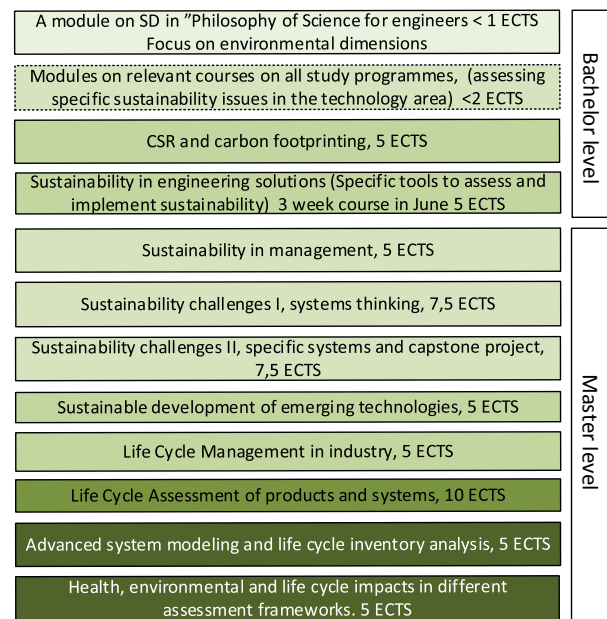


Fig. 1. Overview of the course curriculum of the QSA division. The very light green are broad sustainability courses, light green are introductory to life cycle thinking and simple LCA. Dark green are dedicated LCA courses with the two very dark colored being for the environmental sustainability expert

### 3.1. Bachelor level

At the bachelor level, sustainability is generally introduced to all students in a 4-hour module in the course "Philosophy of Science for Engineers" (<http://kursen.dtu.dk/course/42610>). This is a mandatory course for all bachelor students at DTU and is attended by 250-350 students each semester. A 1½ hour lecture focuses on providing an understanding of environmental sustainability and the engineers' role in achieving or improving environmental sustainability, e.g. through the IPAT\* equation [8]. This lecture is followed by discussion exercises.

The three other course types at the bachelor level introduce life cycle thinking to different extents. The first introduces

\* The  $I = P \cdot A \cdot T$  equation tells that the global environmental impact (I) can be seen as a product of the total population (P, person), the average affluence of the population (A, e.g. GNP/person), and the environmental intensity of the technology producing the goods the population consume (T, e.g. Impact/GNP). Engineers have a central role in reducing the factor T.

LCA in the context of a specific technology, the second focuses on climate change impacts in a life cycle perspective (carbon footprint), and the third introduces simple Life Cycle thinking and how to implement “sustainable” solutions.

As part of the QSA strategy, we aim to reach out to the different bachelor study programs and introduce the students to Life Cycle Thinking and simplified LCA. This is carried out in relation to sustainability issues relevant to students’ specific fields of studies through integration into technology specific courses. This has so far been accomplished for civil engineering, where QSA contributes significantly to two courses. In one of these courses, “**Optimization, resources, and environment**” (<http://kurser.dtu.dk/course/11968>) the general objective is to present basic principles of life cycle thinking and assessment for civil engineering projects. LCA plays an even more important role in the other course, “**Sustainability and Life Cycle Assessment**” (<http://kurser.dtu.dk/course/11997>). This introduction of LCA at the bachelor level has proven valuable for the students as a teaser for more advanced studies. Teaching LCA at the bachelor level has also proven challenging mainly due to the lack of easily understandable and reliable product system modelling software. At DTU we have successfully applied the free product version of Quantis Suite 2.0 [9]. This software choice allows for simplified product system modelling.

In addition, two sustainability training related bachelor courses are coordinated by QSA and have a broader application field. The course “**CSR and Carbon Footprinting for corporations**” (<http://kurser.dtu.dk/course/42352>) introduces students to the private sector’s role in a global sustainability context and introduces “SDG Compass” as a tool for this [10]. As another concrete tool, a considerable part of the course is devoted to learning how to elaborate a corporate carbon footprint (CFP) [11,12].

The course “**Sustainability in engineering solutions**” (<http://kurser.dtu.dk/course/42340>) runs full time during three weeks, which makes it well suited for students’ own project work. The course follows a “sustainable design” method [13] aiming for students to learn not just sustainability assessment methods but also how to synthesize new solutions. The students work on real life cases e.g. sustainable solutions in DTU’s campus facility management. The course is attended by app. 60 students per year broadly representing all study programs at DTU, and the course has been described in some detail by Olsen et al. [14].

### 3.2. Master level – generalist competences

The 28 master programmes at DTU encompass 120 ECTS points (European Credit Transfer and Accumulation System credits). General competences (30 ECTS) and Technological specialization (30 ECTS) courses are specific for each master’s programme. These are the courses that define the programme and are often technology-specific. The electives can be chosen freely among the variety of master courses offered at DTU.

There is no dedicated study programme at DTU with specific emphasis on sustainability and LCA. The programmes that are closest to a sustainability-focused education are the Master of Environmental Engineering and the Master of Sustainable Energy. Therefore, it is difficult to suggest a single recommended progression from the bachelor level through several master level courses to become a sustainability and/or LCA expert (the sustainability expert having a broader perspective). Unless some of the courses form part of the programme as mandatory general competences or technological specializations they may be difficult to prioritize since students only have the possibility to choose 30 ECTS from elective courses.

The introductory course to sustainable engineering at master level is the 5 ECTS course “**Sustainability in management**” (<http://kurser.dtu.dk/course/42351>) which is a mandatory general competence course for students of the master’s programme “Industrial Engineering and Management”. It aims to prepare the students for the sustainability challenges in relation to their future work as technical experts or managers.

“Copenhagen Sustainability Initiative” (CoSI) is a collaboration between Copenhagen Business School, University of Copenhagen, and DTU. Two courses have been developed aiming to address the need for multidisciplinary in solving sustainability challenges and to bridge the gaps between natural science, technology and business solutions. The following two courses are offered as electives to students from all three universities. The first course, “**Sustainability challenges I, Systems thinking**” (7.5 ECTS, <http://kurser.dtu.dk/course/42349>), provides the theoretical background and concepts such as “Earth system/Planetary Boundaries”, “Production systems”, and “Business interaction systems”. In the second course, “**Sustainability Challenges II, Specific systems and capstone project**” (7.5 ECTS, <http://kurser.dtu.dk/course/42350>), students collaborate in multidisciplinary, i.e. multi-university, project teams. The teams develop solutions for project cases from the three sustainability challenges areas “Food”, “Waste”, and “Energy”, on topics like reduction of plastic bag waste in the seas, or urban farming to secure food supply.

Considering that many technology developers (i.e. engineers) are being educated at DTU, the course “Sustainable development of emerging technologies” (5 ECTS) aims to offer the students knowledge about various sustainability aspects they should consider when developing new technologies. The course is project based and has very few lectures on topics driven by the students knowledge gaps or requests.

Also at an introductory master level but with more emphasis on the life cycle perspectives and organizational decision-making is the course “**Life Cycle Management in industry**” (5 ECTS, <http://kurser.dtu.dk/course/42377>), which focuses on application and implementation of Life Cycle Management (LCM) in industrial organizations. In terms of the progression of sustainability knowledge and skills, the LCM course supplements the full LCA course (see below) and may be taken before or after following the LCA course.

### 3.3. Master level – quantitative assessment of sustainability

The LCA-course “**Life Cycle Assessment of Products and Systems**” (10 ECTS, <http://kurser.dtu.dk/course/42372>) is integrated into 7 master study programmes such as the environmental engineering and the Sustainable energy programmes as a technological specialization or general competence course (meaning that it is not included in the 30 ECTS electives and therefore easier for the students to prioritize).

The LCA course is designed for students to acquire a thorough understanding and hands-on practice of the LCA methodology. The strength of the course stems from the optimized alignment between theory acquisition (now relying on a textbook by Hauschild et al. 2018 [15]), individual assignments progressively introducing the various phases of LCA, frequent feedback provided to the students, and a case study application to experience the issues and challenges of conducting LCAs. Over the past 20 years, more than 1000 students have passed through the LCA course (approx. 80-100 students follow it each year), and 192 case studies have been performed in collaboration with 104 industries and organizations[16].

As further specialization in quantitative sustainability assessment, two more courses are offered at the master level. Students can take one or both courses depending on their choice of study specialization.

The course “**Advanced system modeling and life cycle inventory analysis**” (5 ECTS, <http://kurser.dtu.dk/course/42375>) is intended for students pursuing LCA-expertise/quantitative sustainability assessment competencies and is typically taken by 15-25 students/year. A special focus is given to inventory data, therefore the course introduces advanced inventory topics such as temporal scope modelling, inventory data modelling as well as application of dynamic inventory data in relation to product system modelling. The students also become acquainted with internationally acknowledged standards, modelling approaches and accompanying tools.

The course “**Health, environmental, and life cycle impacts in different assessment frameworks**” (5 ECTS, <http://kurser.dtu.dk/course/42378>) provides students with the necessary knowledge to evaluate impact assessment principles, build and apply mathematical models and develop impact pathways. This enables them to apply and interpret

impact assessment results in specific decision contexts. 20-30 students typically take this course each year.

### 3.4. PhD Level

Toxicity related impacts are among the most complex and difficult to characterize impacts in LCA and elsewhere, not least due to the large variety of potentially toxic chemicals that might be relevant. To address current toxicity assessment challenges, apply the scientific consensus characterization framework USEtox for chemical emissions [17] and to adapt the framework for consumer and occupational exposure [18], a dedicated **USEtox PhD Summer School** (5 ECTS) is offered at DTU (see <http://usetox.org/Summer-School> for further details). This course offers the highest level of specialization within the sustainability assessment course curriculum offered by DTU’s QSA division.

### 3.5. Other relevant courses at DTU

There are several other courses offered at DTU that contribute to building sustainability and LCA competencies in DTU students. For instance, there is a dedicated LCA course only for Bachelor in Engineering. Also, the Department of Environmental Engineering offers a master level course on LCA of solid waste as well as two PhD courses on LCA of solid waste (with focus on their system modelling tool EASETECH [19]) and LCA of bioenergy, respectively. Furthermore, many of the courses at this department address environmental sustainability to some extent. For example, the master programme “Sustainable energy” (offered by the Management Engineering department) also includes several courses with a sustainability view, e.g. the general competence course “Energy and sustainability”. QSA staff also introduces sustainability and/or LCA at a few courses at different departments, e.g. DTU Aqua and DTU food, focusing on fisheries/aquaculture and food, respectively, motivating the students to seek deeper sustainability competences in some of the other courses mentioned previously.

Table 1 provides an overview of the course curriculum and how the courses progress from introducing basic level competency, ultimately culminating at the level of expert sustainability assessment and/or methodology development.

Table 1: Overview of QSA education outcomes and progression.

Courses	Main learning objectives	Main acquired competences	Teaching methods	Level of progression
Bachelor level				
42610 A single 4 hour module.	Understanding environmental sustainability Bloom’s level 1	Recognize sustainability challenges and engineers’ role in achieving or improving environmental sustainability	Lecture and group discussions	Introduction to sustainability
11968 App. 1 ECTS	Comprehend LCA concepts Apply to and analyse simple civil engineering systems Bloom’s level 1-3	Identification and optimization of resource consumption and environmental impacts for civil engineering projects	Lectures and exercises	Introduction of life cycle perspective Simplified modelling
11997 App. 2 ECTS	Comprehend LCA and ecodesign concepts Apply to and analyse simple civil engineering systems Bloom’s level 1-4	Quantification and analysis of environmental impacts from buildings, components and products eco-design (synthesis-oriented)	Lectures and exercises	Introduction to life cycle perspective Simplified modelling and synthesis



42352 5 ECTS	Comprehend companies' work with corporate social and environmental responsibility (CSR) Elaborate a corporate carbon footprint Bloom's level 2-6	Knowledge and capabilities regarding CSR and CFPs	Lectures and exercises. Case based analysis Case project based group work.	Introduction of company CSR perspective and evaluation of reporting CFP as a simplified LC tool
42340 5 ECTS	Comprehend and analyse sustainability in a life cycle perspective Synthesize new sustainable solutions Bloom's level 1-6	Assessing sustainability using simple methods Synthesize new solutions Understanding how e.g. different actors play a role in implementation of sustainable measures	Lectures and exercises. Case (real life) project based group work	Analysis of simple real life cases Synthetization and evaluation of solutions
Master level				
42351 5 ECTS	Analyse and evaluate sustainability strategies Analyse and build sustainable business models Comprehend LCA and circular economy Bloom's levels 2-6	Critical reflection on companies' CSR work Introducing sustainability into business models	Lectures and exercises Project based group work	Critical evaluation of company strategies Comprehension of LCA and Circular economy Simple LCA
42349 and 42350 Each 7.5 ECTS	Comprehend and evaluate sustainability in a holistic perspective Evaluate key characteristics of energy systems, waste and recycling systems, and natural resources, food and agriculture systems Bloom's level 2-6	Operate and communicate in multi-disciplinary teams that seek to tackle and find innovative solutions to the complex sustainability challenges society and business face.	Lectures and exercises Project based group work	Understanding the multidisciplinary of sustainability issues and their solutions Interdisciplinary collaboration Life Cycle thinking assessment
42348 5 ECTS	Analyse and evaluate environmental, social and economic sustainability of emerging technologies Bloom's level 2-6	Acquiring an overview of sustainability aspects to be considered when developing new technologies. Apply a number of tools (e.g. simple LCA, actor network analysis, strategy canvas etc.)	Case based learning Project based group work	Understanding the multidisciplinary of sustainability issues Application of tools to evaluate sustainability
42377 5 ECTS	Identify instruments for LCM Analyse the sustainability activities of an organization Evaluate and develop sustainability strategies Bloom's level 2-6	Application and implementation of Life Cycle Management (LCM) in industrial organizations Application of instruments e.g. ecolabels, ISO standards, Carbon Footprints, Product Lifecycle Management (PLM) systems Progress measurement (e.g. by defining performance indicators)	Lectures and exercises Project based group work	Critical evaluation and development of company strategies Knowledge and application of LCM instruments
42372 10 ECTS	Comprehend and evaluate LCA methodology and LCA studies Explain applications of LCA  Bloom's level 2-6	Theoretical foundation of and hands-on practice with LCA methodology Development of full LCA studies, perform basic sensitivity and uncertainty analysis and interpretation and communicate LCA results.	Lectures and exercises Case based learning from real life cases with industry and other organizations Project based group work	LCA expertise for industry, and public agencies, NGOs, etc.
42375 5 ECTS	Analyse and solve complex LCA problems by development and application of parameterized and modular product system models. Implement parameterized inventory models Bloom's level 3-6	Expertise in analysing inventory models and in adapting models and software to specific application areas	Lectures and hands-on work	Proficiency in conducting a complete LCA study by application and development of real life modular and parameterized models and advanced inventory and characterization models.
42378 5 ECTS	Analyse real-life sustainability questions by applying different methods with focus on LCA Evaluate sustainability assessment methods in different decision contexts Interpret and communicate complex sustainability results Bloom's level 3-6	Application of common LCA software tools and databases Performing full environmental LCA studies Developing new data and impact pathways	Case-based learning (real industry cases) Problem-based learning (sustainability problem focused analysis)	Detailed understanding and training of LCA software, data and methods Ready for application and implementation of quantitative sustainability tools in industry and policy
PhD level				
PhD (5 ECTS)	Analyse chemical fate, human exposures, and toxicity-related effects Evaluate assumptions, uncertainties and application domains of USEtox Bloom's level 4-6	Application and modification of toxicity characterization methods and models including developing new data and pathways Ranking of chemicals in different science-policy contexts	Case-based learning (participants bring their own cases) Interactive discussions and cross-fertilization (case-centred discussion of all participants)	Specific high-level training in toxicity characterization and interpretation methods and models Ready for implementation, adaptation and development of toxicity tools in industry and policy practice

#### 4. Discussion

As a way to qualify the goals of the strategies at both the university level (DTU strategy) and the division level (QSA strategy) and to guide the process towards reaching them, QSA has proposed learning objectives for the training of engineering students at DTU in evaluating sustainability with core focus on LCA. Inspired by the development of learning outcomes for sustainability at Royal Institute of Technology (KTH) in Stockholm [20], three groups of learning outcomes have been suggested for students graduating from DTU:

1. Definition and key elements of sustainability
2. Quantitative assessment of sustainability with special focus on environmental life cycle assessment
3. Sustainability in business and management

Different levels of competences are required depending on whether the student aims for the level of technology expert/leader (generalist) or sustainability specialist.

As shown in table 1 the courses offered by QSA present a palette that targets each of the different groups of the learning outcomes. They progress from providing a very basic understanding of sustainability to the specialist courses targeting students that aspire to a career as a sustainability specialist, ensuring a progression that supports reaching the required different levels of competences. The students' achievement of the overall learning outcome is evaluated through the achievement of learning outcomes in each single course.

#### 5. Conclusions

Considering that QSA counts a teaching faculty staff of six and that DTU has app. 11,000 engineering students, the strategy of QSA can be seen as rather ambitious. New strategies for teaching the students have to be employed, e.g. an integration into the technological courses in the various study programmes probably achieved by a continuous embedding of sustainability through building sustainability knowledge in faculty staff all over DTU, e.g. through workshops, seminars etc. Such a dedicated effort has been at least partly successful in other universities such as Chalmers University of Technology and Technological University of Delft [21]. Strategic development of the relevant courses, e.g. by introducing e-learning, efficient methods of student evaluation etc. could compliment this approach.

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